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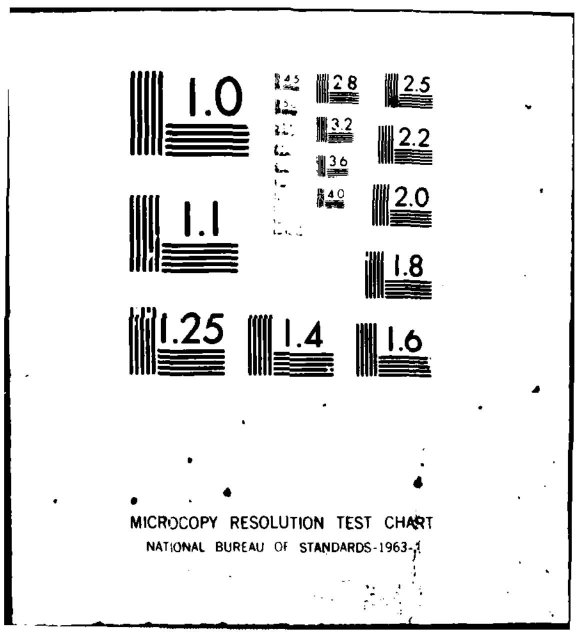
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PRECIPITATION ESTIMATION FOR MILITARY HYDROLOGY

APRIL 1980

By

BRUCE T. MIERS

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US Army Electronics Research and Development Command
ATMOSPHERIC SCIENCES LABORATORY
White Sands Missile Range, NM 88002

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The military hydrologist has been given the responsibility for river stage and flood forecasting, soil trafficability, and weather observations pertinent to hydrologic problems in the battlefield area forward of Division command elements. In tactical situations, the emplacement and monitoring of gages or sensors in hostile territory are not practical; therefore, the military hydrologist must rely on indirect means of estimating precipitation. This report reviews current methods of estimating precipitation (models, radar, satellite) and presents six

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20. ABSTRACT (Cont)

case studies of precipitation estimation using geostationary operational environmental satellite imagery. It is concluded that the military hydrologist (in the 1980's) can best meet his requirements through the use of calibrated weather radar.

CONTENTS

INTRODUCTION

Joint Regulation AR 115-10/AFR 105-3 assigns the Army the responsibility for river stage and flood forecasting, soil trafficability, and weather observations in the battlefield area forward of Division command elements. Since rainfall is the dominant driving force for hydrologic phenomena of military significance, methods to measure or estimate precipitation are important. In hydrology, rainfall is important when averaged in space and time. Often small-scale variability is so large that instantaneous point values have little relation to the important averaged values. The extent of averaging desired depends on the available observations and the field applications. To the military hydrologist, areas where no precipitation is falling are also important. Rainfall values that are of most interest for any single area are the mean and peak amounts. In tactical situations, the emplacement and monitoring of gages or sensors in hostile territory are not practical; therefore, the military hydrologist must rely on numerical forecasts or remote sensors (i.e., radar or satellite-borne sensors) for his data. Each of these methods has strengths and limitations in its use for military hydrologic problems. This report will discuss the above methods or precipitation estimation and present six case studies of precipitation estimation with meteorological satellite data (geostationary operational environmental satellite [GOES]).

NUMERICAL MODELS

Currently there is no operational or research moisture analysis model that is automated and that provides both humidity and hydrometer analyses. One approach under study at this time attempts to combine an operational nephanalysis scheme[1] that gives fractional cloud coverages in layers with a humidity analysis routine for conditions between clouds and a precipitation analysis routine that includes radar data. Models that can be used to forecast precipitation must contend with three scales of atmospheric motions. The first is the regional or synoptic scale (2000 km x 2000 km) where rainfall accumulations are averaged over 6 hours and river stage changes (major waterways systems) are observed about 24 hours after the occurrence of a rainfall event. The second scale is the mesoscale (200 km x 200 km) where precipitation is averaged over 1 hour and streamflows (intermediate waterways) begin to change about 6 hours after the rainfall event. The third scale is the microscale (2 km x 2 km) where the precipitation is averaged over 15-minute intervals and the impact is felt about 1 hour after the event (small streams). Therefore, for a numerical model to be effective for military hydrologic purposes, regional, mesoscale, and microscale models

[1]F. K. Fye, 1978, The AFGWC Automated Cloud Analysis Model, AFGWC-TM-78-002, Air Weather Service

must be nested into a coherent system. These scales must be considered simultaneously because atmospheric phenomena are dynamically coupled and change continually.

Current research models have shown limited success in correctly placing the precipitation areas and estimating their magnitudes.[2] These problems are thought to be caused in part by the data used to initialize the model, while the physics of the model contributes the remainder. Because it is not possible to simulate all scales on today's computers in detail, it is necessary to parameterize the subgrid scale effects of convection. One type of parameterization emphasizes the lateral mixing of cloud substance into the environment as the principal means of atmospheric sensible temperature and vapor changes, while another method emphasizes the cumulus induced environmental subsidence as the principal mechanisms. Both methods require a closure assumption to determine the cloud mass or percent areal coverage and information about profiles of in-cloud variables such as temperature, moisture, and mass.

A consistent, comprehensive system that maximizes the positive interaction between classes of models must be developed for numerical models to be of significant benefit to the military hydrologist. It appears that this will not be accomplished before the 1990 time frame.

Radar has been used for nearly 30 years to estimate rainfall. Utilization of radar by the military hydrologist has been hampered by military doctrine, a misunderstanding of the ability of the radar to measure rainfall, the factors that contribute to the observed errors, and the importance of calibration. The primary source of error in radar estimates of rainfall is the variations in the Z-R relationship (radar reflectivity versus rainfall rate) caused by microphysical and kinematic processes that affect drop-size distribution and drop-fall speeds.

Rainfall estimates using radar data were often found to be in error by a factor of two or more when compared with a rain gage network.[3] Estimates are generally improved when rain gage observations are used to calibrate quantitative radar data (errors in the 10 to 30 percent range). Since rain gages are used to calibrate radar rainfall estimates, errors in gage measurements should be examined. The major cause of error in gage measurements is from turbulence and windflow-

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[2] D. J. Perkey, 1976, Prediction of Convective Activity using a System of Parasitic-Nested Numerical Models, NASA Contractor Report NAS8-31235, NASA, p 144, Washington, DC 20546

[3] C. G. Collier, T. W. Harrold, and C. A. Nicholass, 1975, "A Comparison of Areal Rainfall as Measured by a Raingage-Calibrated Radar System and Raingage Networks of Various Densities," Proceedings, 16th Radar Meteorology Conference (Houston), AMS, pp 467-472, Boston, MA

about the gage. Larson and Peck[4] reported an error of 12 percent (less rain) for a wind of 5 m/s^{-1} and 19 percent at 10 m/s^{-1}. Variations in rainfall patterns cause errors in areal rainfall estimates. Sampling error decreases with increasing area size, increasing time period, increasing gage density, and increasing rainfall amount.[5] Usually errors in gage measurements of areal rainfall are about 5 percent for convective storms.[6] However, Woodley et al[7] reported errors of 10 to 40 percent, depending on rainfall amount. Adjustments for radar derived thunderstorm rainfalls by a single centrally located gage reduced the error from 51 to 35 percent.[8] Jatila and Puhakka[9] found that no improvement was made for single gage adjustments in stratiform rains, but errors in convective rainfalls were lowered from 43 to 25 percent.

In general, current radars tend to overestimate light rainfall and to underestimate heavy rainfall. Despite these limitations, the weather radar provides the military hydrologist with spatially and temporally continuous measurements for estimating streamflows and soil moisture.

SATELLITE

Over the past 10 years, the estimation of precipitation by using satellite imagery (visible, infrared, microwave) has met with varying degrees of success. Microwave measurements from radiometers on board the Defense Meteorological Satellite Program (DMSP) and NIMBUS*

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[4] L. W. Larson and E. L. Peck, 1974, "Accuracy of Precipitation Measurements for Hydrologic Modeling," Water Resour Res, 10:857-863

[5] A. D. Nicks, 1966, "Field Evaluation of Rain Gage Network Design Principles," International Assoc Sci Hydrol Pub, 67:82-93

[6] F. A. Huff, 1971, "Evaluation of Precipitation Records in Weather Modification Experiments," Advances in Geophysics, 15:59-134

[7] W. L. Woodley, A. Olsen, A. Herndon, and V. Wiggert, 1975, "Comparison of Gage and Radar Methods of Convective Rain Measurement," J Appl Meteorol, 14:909-928

[8] J. W. Wilson, 1970, "Integration of Radar and Rain Gage Data for Improved Rainfall Measurement," J Appl Meteorol, 9:489-497

[9] E. Jatila and T. Puhakka, 1973, "On the Accuracy of Radar Rainfall Measurements," Geophysica, 12:127-140

*A National Oceanic and Atmospheric Administration (NOAA) meteorological satellite program

satellite series represent the most direct satellite-borne measurement of precipitation droplets. However, these sensors have poor resolution in time (twice daily sampling) and space (field of view about 900 km^2 at subsatellite point) along with problems of surface emission overland. The thermal emission by cloud and precipitation is associated with the microwave absorption characteristics of media composed of liquid water drops. For long wavelengths and small drop size, the absorption, and therefore the radiance in the Rayleigh-Jeans spectral region (4 to 28 micrometers), is directly proportional to liquid water integrated along the radiometer beam axis. For the larger precipitation particles, the radiance will no longer increase in a manner proportional to the liquid water content and may even decrease as a consequence of the importance of scattering, which becomes significant at high microwave frequencies. There is a need for multiwavelength radiometers for the interpretation of the microwave radiance observed by satellites in precipitation areas.

Over the ocean, which has low emissivity, the increase of radiance due to hydrometers is large and allows direct mapping of precipitation areas by simple satellite imagery obtained from scanning microwave radiometer data. Overland, which is associated with more emissivity, the presence of hydrometers will produce a decrease of earth-atmosphere emission. By considering radiances observed at different wavelengths, it may still be possible to identify and map precipitation areas; however, it is certainly difficult to estimate precipitation intensity and reliability. Theoretical and experimental results obtained overland at 37 GHz[10] indicate that radiances emerging from rain clouds are less than those emerging from warm land surfaces. These results also show that cool land features such as lakes and flooded areas depend markedly on polarization whereas those emerging from rain clouds do not. Such differences in the polarization of emission may offer additional means to recognize the presence of precipitation overland from microwave radiance data.[11]

Visible and infrared wavelengths predominantly respond to the relative abundance of cloud droplets and not to precipitation size particles. There is good evidence that visible and infrared wavelengths provide indication of the existence of rainfall; however, estimation rainfall rate is not possible at this time.

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[10]R. C. Savage and J. A. Weinman, 1975, "Preliminary Calculations of the Upwelling Radiance from Rainclouds at 37.0 and 19.34 GHz," Bull Amer Meteorol Soc, 56:1271-1274

[11]R. Lhermitte, 1979, "Advancements in Remote Sensing of the Atmosphere," Reviews of Geophysics and Space Physics, 17:1833-1840

Scofield and Oliver[12] have developed a decision tree method of rainfall estimation where a meteorologist subjectively evaluates several visible and infrared imagery parameters and extracts meteorological information from the synoptic charts to make point rainfall estimates. This technique is used to a limited extent by the National Weather Service in their flash flood warning system. Griffith et al[13] developed an estimation technique that defines a cloud area by using an infrared or visible cutoff value for a sequence of clouds. Their premise is that rain from convective clouds can be determined from a life history of the area of convective cloud. Their method results in an equivalent radar echo as an intermediate result of an estimate of rain amount.

A combination of microwave, visible, and infrared satellite-borne sensors to estimate rainfall over mesoscale areas will depend upon the development of large-size microwave antennas (that can be placed on geostationary satellites). These antennas will be capable of producing narrow beams comparable with those available for infrared sensors. The 1990 time frame seems feasible for this engineering accomplishment.

DESCRIPTION OF DATA

Digital satellite data were obtained at 15-minute intervals from the GOES-E satellite which has a subsatellite point of 75° west. The raw visible data have 6-bit resolution and provide relative brightness values from 0 to 63. The raw infrared data have 8-bit resolution that provides 1°C equivalent blackbody temperatures of cloud tops whose temperatures are colder than -31°C. For temperatures warmer than -31°C, the resolution is 0.5°C. Satellite data sectors for the various days studied were days that were designated Research Rapid Scan Days by the National Environmental Satellite Service. The size of each data pixel varied according to the viewing angle of the satellite. The infrared pixels (at these latitudes and longitudes) ranged in size from about 75 km^2 to 45 km^2, while the visible pixels varied from about 4.5 km^2 to 1.5 km^2. This size variance must be considered when areal rainfall is being estimated. A height projection or height skew error must also be considered, due to the satellite projecting cloud tops away from their earth-normal vector positions. The satellite data were processed on a minicomputer with a video refresh system. The advantage of this system is the capability to display in an image form the digital satellite data without losing its quantitative value. Another important feature of this system is recognition on the image of landmarks for navigation of

[12] R. A. Scofield and V. J. Oliver, 1977, "A Scheme for Estimating Convective Rainfall from Satellite Imagery," NOAA Tech Memo NESS 86, NOAA-NESS, p 47, Washington DC

[13] C. G. Griffith, W. L. Woodley, P. G. Grube, D. W. Martin, J. Stout, and D. Sikdar, 1978, "Rain Estimation from Geosynchronous Satellite Imagery-Visible and Infrared Studies," Mon Wea Rev, 106:1153-1171

the satellite data. Through various transformations, the satellite images were adjusted to conform to a standard Environmental Data Service (EDS) map projection for comparison with the rain gage data from EDS publications.

SATELLITE OBSERVED SIGNATURES RELATING TO RAINFALL

Reynolds and Smith[14] developed a list (table 1) of satellite parameters that could be used in a rainfall estimation scheme. Scofield and Oliver's[12] decision tree method is affected by cloud base level, the height of the tropopause, and orographic effects. Generally, these researchers have found that rainfall does tend to occur under regions of higher albedos and colder cloud tops, but that the intensity of the rainfall is not well-correlated to either brightness or temperature. Eddy and Hembree[15] have shown that, by fitting nonlinear autovariance and cross-variance functions to space-time covariance values calculated from satellite data, certain convective complex characteristics (motion, growth, and decay) can be determined. Miers[16] showed the results of these computations for a complex over the Texas Panhandle.

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[14]D. W. Reynolds and E. A. Smith, 1979, "Detailed Analysis of Composited Digital Radar and Satellite Data," Bull Amer Meteorol Soc, 60:1024-1037

[12]R. A. Scofield and V. J. Oliver, 1977, "A Scheme for Estimating Convective Rainfall from Satellite Imagery," NOAA Tech Memo NESS 86, NOAA-NESS, P 47, Washington DC

[15]A. Eddy and L. Hembree, 1978, Space-Time Sampling from SMS Satellite Data Required to Define Convective Storms, Atmos Sci Lab Contractors Rpt No DAAG29-76-D-1000, p 38

[16]B. T. Miers, 1979, Precipitation Estimation Using Satellite Data, ASL-TR-0039, p 46, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

TABLE 1. SATELLITE SIGNATURES RELATING TO RAINFALL

ALBEDO

1. Magnitude not well related to precipitation intensity but does locate areas of rainfall with high spatial and temporal resolution using brightness thresholds.

2. Areas of rainfall will be indicated prior to cold clouds developing (as indicated in the infrared) and may precede rainfall at the ground.

3. Line structure of clouds and cloud mergers imply higher precipitation rates.

4. Duration of bright clouds over an area implies higher rainfall totals.

5. Rate of change of brightness indicates developing clouds and thus rainfall.

CLOUD TOP TEMPERATURES (CTT)

1. Magnitude of CTT not well related to precipitation intensity. At specific locations, however, the coldest tops do delineate rain/no-rain areas.

2. Development of cold tops in the infrared data tends to lag radar echo development.

3. Chosen thresholds in the infrared should be related to ambient environment and related tropopause temperature.

4. Under low wind shear, rainfall occurs underneath the coldest tops.

5. Rate of change of CTT can imply increasing or decreasing rainfall intensities.

6. Average area of coldest cloud tops between half-hour images relates well to area over which rainfall occurs.

CASE STUDIES

The locations, dates, and times of the case studies are given in table 2. Only hourly precipitation values were used to determine the relationship between rainfall and the satellite data. The data in table 3 represent the number of occurrences of a particular rainfall amount related to the average cloud top temperature over that station. For example, in the Gulf Coast case there were eleven occurrences of rainfall between 0.11 and 0.20 in/hr when the average infrared cloud top temperature over the rain gage was colder than -75°C.

The tabulated data show that larger amounts of rainfall are associated with the colder cloud top temperatures. Also when normalized brightness values of these clouds were studied, the greater rainfall amounts usually occurred under the brightness cloud tops. Further analysis indicated that rainfall intensity was not well-correlated to either cold cloud tops or higher albedos. Larger rainfall amounts also tended to occur when convection was vigorous enough to penetrate the tropopause. The storms that penetrate the tropopause also exhibit strong infrared cloud top temperature gradients, particularly on the southern portion of the cell. The Gulf Coast case was an example of this type storm. Three cases of rainfall exceeding 2 in/hr were recorded in the storm.

Other storm features such as movement, growth, and decay have been determined by modelling covariance and cross-covariance functions of the satellite data.[16] For the visible and infrared data to be valuable in estimating rainfall, a determination has to be made for each geographical area as to the range of rainfall values to be assigned as a function of cloud temperature, temperature gradient, tropopause height, or any of the other features listed in table 1. A data compositing technique[14] using a satellite, radar, and rain gage would yield the best results.

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[16] B. T. Miers, 1979, Precipitation Estimation Using Satellite Data, ASL-TR-0039, p 46, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

[14] D. W. Reynolds and E. A. Smith, 1979, "Detailed Analysis of Composited Digital Radar and Satellite Data," Bull Amer Meteorol Soc, 60:1024-1037

TABLE 2. CASE STUDIES INFORMATION

Location	Date	Time
Mississippi and Alabama	4 April 1977	1700Z to 0000Z
Iowa and Illinois	5-6 May 1977	2300Z to 0100Z
Iowa and Illinois	15 May 1977	1700Z to 0000Z
Texas Panhandle and Western Oklahoma	20 May 1977	1800Z to 2100Z
Mississippi and Alabama	28 July 1977	1730Z to 2200Z
Gulf Coast (LA, MS, AL, FL)	3 May 1978	1700Z TO 0000Z

TABLE 3. OBSERVED RAINFALL RATE VERSUS CLOUD TOP TEMPERATURES

(Number of Occurrences for each Category are shown)

Observed Infrared Temperature Range (°C)	Observed Rainfall Rate (in/hr) 0	0-.10	.11-.20	.21-.30	.31-.40	.41-.50	.51-1.0	1.01-1.5	1.51-2.0	>2.0
Colder than -75	2	7	11	7	0	3	5	3	3	1
-70 to -75	3	5	13	6	4	1	5	2	0	2
-65 to -70	11	9	8	5	3	1	1	0	0	0
Gulf Coast (LA, MS, AL, FL) (3 May 1978)										
Colder than -67	4	4	3	1	2	5	5	5	0	0
-65 to -67	8	10	3	2	2	0	0	0	0	0
-63 to -65	6	3	2	1	5	0	1	0	0	0
Texas Panhandle and Western Oklahoma (20 May 1977)										
Colder than -67	3	0	2	2	1	1	1	0	0	0
-65 to -67	4	4	2	2	1	0	0	0	0	0
Warmer than -65	4	6	1	2	0	0	2	0	0	0
Iowa and Illinois (5, 15 May 1977)										
Colder than -63	5	4	1	0	0	1	2	3	0	0
-60 to -63	4	2	2	0	0	0	1	0	0	0
-55 to -60	3	5	1	0	0	0	2	0	0	0
Warmer than -55	5	4	2	1	2	0	1	0	0	0
Mississippi and Alabama (4 April 1977)										
Colder than -75	3	3	0	0	0	0	0	0	0	0
-70 to -75	4	2	1	0	0	0	1	1	0	0
-60 to -70	4	12	2	2	2	0	0	0	0	0
-50 to -60	6	4	1	1	1	0	0	1	1	0
-40 to -50	8	6	0	2	0	0	1	1	0	0
Warmer than -40	12	0	0	0	0	0	1	0	0	0
Mississippi and Alabama (28 July 1977)										

RAINFALL ESTIMATE ACCURACIES (SATELLITE DATA)

Lovejoy and Austin,[17] using a weather radar as a standard, computed the root mean square (RMS) error in satellite-determined estimates to be about 49 percent. Their hypothesis is that satellite data should be used first to estimate rain areas and then to estimate rain amounts for these areas by multiplying by a suitable average rain rate. If periods of accumulation of more than 1 hour are used, the error can be reduced more. As seen in table 3, there were many cases where no rain was measured, even under the coldest clouds. This can be explained by the fact that clouds associated with rainfall tend to form uniform cirrus anvils over the gages and mask out detail one might see from satellite data. Thus, GOES visible and infrared data apparently are good for determining rain areas but poor for determining rain rates.

SUMMARY

From the data presented in this report and the findings of other researchers, the GOES visible and infrared data were found to be good for determining rain areas but poor for determining rain rates. To adequately describe the rainfall from convective complexes (using satellite data), the development of an interactive (man-machine) system and a modification of the Scofield-Oliver scheme would yield the best results. A compositing technique using satellite and radar imagery[14] would decrease the estimation error. Variations in rainfall rate about its long-term value also limit the use of an estimation technique that uses only satellite data.

Precipitation estimation using numerical models will be of marginal value to the military hydrologist until microscale, mesoscale, and regional scale models are nested into a coherent operational system. Even after a system is developed, validation of the system will be uneven, and its ultimate power and limitations will not be known until after several years of use and implementation of application programs in follow-on projects.

The military hydrologist (in the 1980's) will find that the most accurate remote sensor for estimating precipitation is a calibrated radar. This is especially true since techniques using satellite imagery are limited to convective precipitation cases. At the present time,

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[17] S. Lovejoy and G. L. Austin, 1979, "The Sources of Error in Rain Amount Estimating Schemes from GOES Visible and IR Satellite Data," Mon Wea Rev, 107:1048-1054

[14] D. W. Reynolds and E. A. Smith, 1979, "Detailed Analysis of Composited Digital Radar and Satellite Data," Bull Amer Meteorol Soc, 60:1024-1037

estimation of stratiform precipitation using satellite data is not feasible. Eddy[18] has shown that data from four rain gages and a calibrated radar can characterize the storm-total rainfall of most weather situations. This minimum amount of equipment can easily be supported in most military operations.

[18]A. Eddy, 1979, "Objective Analysis of Convective Scale Rainfall using Gages and Radar," J of Hydrology, 44:125-134

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